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Electrical demand side contribution to frequency control in power systems: a review on technical aspects

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ABSTRACT

Demand side participation in frequency control in power systems, which leads to reduced reliance on conventional thermal units in procuring essential control functions of future energy networks, has gained increased developments in recent years. In this context, the aim of this paper is to provide a review on various design and control schemes of electrical load contribution to frequency control algorithms; both centralized and decentralized control structures are discussed in details.

The problem of synchronization of certain types of electrical loads and different proposed methods of avoiding it are also presented and discussed. Synchronization, which is a consequence of collective controllable demand response to system disturbances, might put the power system in jeopardy and cause its failure; therefore, in order to fully comprehend the causes and effects of this phenomenon, an investigation of this event in a power grid with high level of controllable electrical loads is necessary.

Contents

1. Introduction

The concept of frequency control in power systems is closely related to balance between power generation and power consumption. Hence, a surplus generated power leads to acceleration in synchronous generators' rotational speed and therefore positive power frequency deviation. On the other hand, an increase in electrical demand or equivalently a sudden loss of a generation unit results in a drop in system frequency. Since the security and reliability of the electrical energy network depend intimately on a well-regulated power frequency signal in the system, it is essential to consider and allocate sufficient amount of reserve to be able to cope with power contingencies. The main idea of frequency regulation in power grids is to surpass the source of trouble (i.e. power unbalance) by means of injecting additional amount of reserve to the system. Traditionally, reserve provision in power

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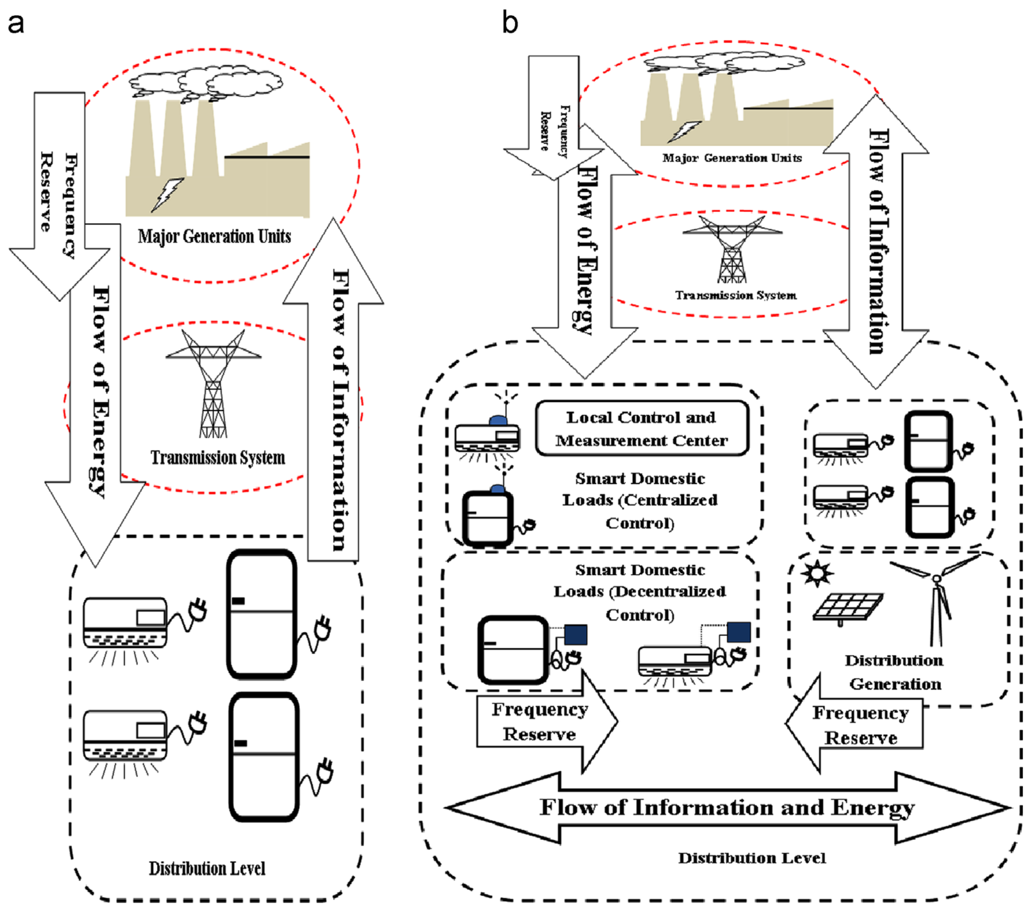

Fig. 1. A comparison of energy networks: a) Conventional network with major thermal power generation units. b) Future networks with high penetration of distributed energy resources and smart loads.

systems has been exclusively the duty of generation units; thus, in face of a power contingency, synchronous generators alter their output power according to magnitude and sign of frequency deviation in the system. This alteration process takes place in three, timely decoupled stages, which form three distinct frequency control levels in power system. A detailed review of load-frequency control and reserve provision in conventional power systems is presented in Refs. [1,2]. Here, we only present a brief review of the main ideas and methods.

Primary frequency control (PFC) is the first regulation measure designed to respond to frequency disturbances, right after a contingency takes place. PFC is exerted by speed governors and is local and decentralized by nature (i.e. control action is based on local generator speed measurements). While PFC is quite effective in limiting frequency nadir, because of its proportional behavior (known as droop), it is unable to eliminate the steady states error in power frequency signal [3]. Thus, a secondary frequency regulation is needed to eliminate the steady states error and restore the system to its pre-contingency status. The secondary control level, which takes place minutes after the PFC, is a centralized control algorithm exerted automatically (automatic generation control or AGC) or even manually by a higher control entity in load-frequency control hierarchy (usually the transmission system operator). Various design processes for this level of frequency control are presented in [4]. The third level of load-frequency control is aimed at economical and long-term redistribution of load among generation units.

The three mentioned control levels, provided by major synchronous generators, are sufficiently capable of regulating system frequency, with a satisfactory efficiency, in traditional energy networks; however, it is widely believed that in future power systems, this will not be true. Present power systems are generally comprised of major thermal units with synchronous machines, which bear the task of generating the bulk of required electrical power; the generated power is then transmitted in long distances and brought to the consumers. This typical picture of energy networks, however, has been changed radically and rapidly in the past years. Increasing penetration of renewable energy resources, such as wind power generators and photo-voltaic technology, along with modern electronic and communication devices, have created a turning point in the structure of modern energy networks (Fig. 1). On one hand, addressing environmental concerns, vast employment of renewable resources leads to lesser dependence on fossil fuel as a major reservoir of energy; on the other hand, utilization of modern data processing techniques in a power system establishes a new level of controllability, and more complicated means of energy management. Thus, the concept of "microgrid" is invented to address the advent of future requirements of electrical energy networks.

A microgrid can be thought of as a cluster of small-scale electrical energy resources (distributed generation units) and loads, connected closely together. A microgrid should be capable of stable operation in islanded mode (disconnected from the national grid), which adds to the complicacy of its control and management. Unlike traditional systems, in a microgrid, generation and demand sides are linked to common busses. Thus, any disturbance on either side (stochastic power output, sudden changes in consumption pattern, etc.), directly affects the other side. Hence, stabilizing and management of microgrids is a critical task which requires thorough investigation. However, this paper is

aimed at addressing frequency control difficulties in power systems and so we will focus on this specific issue.

Frequency control in future power systems will pose a serious challenge. Increasing amount of renewable resources (and consequently falling percentage of synchronous machine employment in power system) leads to decreased rotational inertia in the system. This rotational inertia, which is a direct outcome of rotating masses of generators, is a crucial factor in restricting the rate of change of frequency (ROCOF), right after occurrence of a power contingency in the system [5]. Thus, large systems with higher number of rotating masses (i.e. connected synchronous generators) have a considerable probability to evade collapse after a major disturbance. On the other hand, smaller systems (such as microgrids) with low penetration of thermal units are more susceptible to contingencies. Note that many small-scale distributed generators (such as PVs) do not have a rotational mass to be able to contribute to system inertia, and other generators (such as DFIGs and PMSGs), although having rotational masses, are totally or partially decoupled from power systems, via power electronic converters, and thus, fail to increase system inertia effectively. Hence, higher magnitudes of frequency deviations are predictable in future power systems with large penetration of renewable energy resources. This incoming security hazard has inspired a scientific urge to revise the logic of frequency reserve provision in power systems.

Frequency reserve provision in microgrids and future energy networks have been categorized into three main groups: renewable sources' contribution to frequency control (such as wind generators and electrical vehicles) [6–8], energy storage systems' contribution to frequency control [9,10], and finally, demand side contribution to frequency control. The first two groups mentioned above are both subgroups of the more general and traditional category of generation side's contribution to frequency control. In other words, both of them tend to eliminate power unbalance in the system by means of regulating the output power of a highly controllable generator unit (a distributed generator or an energy storage unit). On the other hand, demand side participation in frequency regulation is a relatively new and still an undeveloped way of reserve provision in power systems and microgrids, and thus merits a thorough investigation.

This paper is intended to provide an in-depth and up-to-date study of various proposed demand management methods that consider participation in frequency control process in a power system. Our aim is to develop a useful perspective of the complexities of the problem and its various practical aspects. We will first go through general capabilities of different demand response programs, and demand side as an ancillary service provider (Sections 2, 3, and 4). In Section 5, a thorough study of different load control algorithms is presented, based on their technical details; the algorithms are classified into two major groups (centralized and decentralized strategies), and their capabilities are compared. And in Section 6, we discuss the secondary effects of demand side participation in frequency regulation, namely long-term frequency oscillations and synchronization. Also, different desynchronizing techniques, which are based on introduction of random processes in load control algorithms, are studied.

2. Demand side management in power systems

Demand management and demand response are new topics in power system research arena. These topics are closely related to the concept of smart grids [11,12]. The term "demand response" refers to those groups of programs in power systems that seek to ameliorate energy network's operating conditions by exploiting demand side control and management techniques. As mentioned previously, utilization of modern and cheap electronic and communication technology in power systems enables a higher level of controllability. When talking about electrical loads, this higher level of controllability results in direct or indirect control of certain types of loads to fulfill power system requirements. By means of two-way communication networks, which allow for the flow of information in both directions (from the operator to consumers and vice versa), it is possible to implement demand management systems, capable of responding (i.e. regulating consumption level) to external signals, such as energy prices. In this way, it is viable for demand side entities to participate in providing ancillary services in the energy network and also assisting the system to move toward an optimal operational mode [13].

Demand response in power systems has been arranged into five classes [14]. These five classes are as follows:

Energy efficiency services: This group of demand side management strategies concentrates on reducing the level of consumed energy by utilizing modern, efficient devices, and without interruption (i.e. limitation or curtailment) in the consumption activity itself; therefore, adjusting consumption profile in power systems at any hour of the day [15].

Price response: Price response programs include management strategies that change consumption levels by means of price-sensitive load controllers. These types of strategies lead to load shifting and load curtailment [16].

Peak shaving: As is cleared by the name, peak shaving programs are concerned with reducing the everyday peak power consumption level and therefore flattening the total consumption curve (load shifting and load curtailment).

Regulation response: This group of strategies includes centralized control algorithms to obtain a power balance in the system, according to a minute-to-minute control basis.

Spinning reserve: This final group of demand management strategies, which is of particular interest to us, includes participation of electrical demand side in frequency regulation of power systems. Thus, this group of strategies is comprised of the fastest responding control algorithms (real-time demand response) to external signals or local measurements compared to other four strategies.

3. Demand side's capability to participate in frequency control

Demand response from household energy consumers is a developing area of power engineering research [17,18]. The idea of fast reserve provision by these consumers, however, is still in the state of infancy. While posing serious challenges, it seems to be presenting promising tools all the same, which will absorb practical and scientific experience in future years.

While power unbalance in electrical energy networks can be diminished by altering the output power of generator units, it can also be decreased by quick changes in consumption pattern. Thus, reserve provision in a power system could be addressed by turning on or off clusters of electrical loads.

Although large-size industrial loads' contribution to frequency control has been reported before [19,20], residential loads' participation in frequency regulation represents unique opportunities that have been addressed recently in technical papers. The most persuasive factor regarding residential power demand's contribution to frequency control is its considerable size on one side and also the ability of certain types of loads to store energy; this trait (load as energy storage system) is a key factor in making thermo electrical residential loads (such as space heaters and refrigerators) a perfect source of frequency reserve. In this context, thermo

electrical loads, which because of their considerable thermal storage capacity are temporarily capable of absorbing surplus power or giving out their previously stored energy, can assist in eliminating the power imbalance in the energy network, right after the occurrence of a power contingency. In this way, these types of loads, which are also controlled by a thermostat, are able to participate in frequency regulation of a power system and to provide extra reserve to overcome frequency deviations.

The main idea, regarding a household electrical load participation in frequency regulation, is that the controllable load is made sensitive to power frequency signal (i.e. it can be turned on or off during a power contingency) and is able to respond to frequency deviations in the system. But the critical point is that residential loads' participation in frequency control, unlike regional blackouts, should have the least disturbing effects on consumer's normal daily activities. In other words, demand side contribution to frequency control should go unnoticed by power consumers; otherwise, if the load control algorithm has a dissatisfying effect on consumers' normal daily activities, they might sign out of the ancillary service provision program.

There are positive statistics that prove thermo electrical loads share a considerable portion of total residential demand; and are, therefore, a proper source of frequency reserve in power system. According to Ref. [21], about 40% of total demand in Europe are household applications, among which are 15% refrigerators and freezers, 22% electric heating systems, 9% electric storage water heaters and 1% room air-conditioners. Another substantial figure is presented in Ref. [22], which states that 61% of total residential electrical consumption in the USA is capable of being controlled for reserve provision purposes, which is able to surpass the reserve provided by thermal units. According to the survey published in Ref. [23], the residential demand of US household in 2009 was comprised of 41.5% space heating, 17.7% water heating, 6.2% air conditioning, 4.7% refrigerators and 29.8% other appliances (including televisions, cooking appliances, computers, etc.). Thus, thermo electric loads, especially space heaters, are a vital portion of total consumption of USA. As an example of a grid with high penetration of renewable energy resources, it is estimated in Ref. [24] that a frequency reserve of 218 MW can be procured by proper management of residential loads in Denmark, which is a considerable amount. Another study, which is aimed at evaluating the demand response programs, states that cold appliances (fridges and freezers) comprise around 32% of the total domestic electrical power consumption in Portugal, while air heating systems with 15% and lighting (12%) are the second and third most widely used types of residential electrical loads [25].

Thus, with the statistics provided above, it is obvious that the prospect of residential electrical demand (especially thermo-electric loads), in providing ancillary services (such as frequency support) to power system is promising, in most developed countries. Already, there are several eminent and successful cases of employment of controllable loads for the purpose of frequency support, in practice. According to Ref. [26], in 2012, around 8% of the total 1200 MW frequency reserve level in the UK was procured from load management programs (both domestic and industrial). Other cases will be discussed in the following sections.

4. Prerequisites for implementation

Actual implementation of load participation in frequency control process is in fact a complicated issue, which requires certain technical and economical structures [27]. Apart from economical incentives that should assist a consumer's trust and interest in the program, there are several necessary technical requirements that are vital to the implementation. They are as follows:

Measurement unit: In a decentralized control structure, a local measurement system is required to evaluate frequency deviation magnitude. Of course in a centralized control algorithm, which does not depend on local measurements, a distributed local measurement system is not needed, and all the measurements are made centrally.

Process evaluation unit: The presence of a process evaluation unit is a mandatory part of demand side management systems, and of the loads themselves. As a simple example, a thermostat is a process evaluation device, which is indispensible for most thermo electrical household types of load. Naturally, every demand management system which is concentrated on providing frequency regulation in power system should take the innate demand side requirements (which are represented by a process evaluation unit) under consideration. For example, a normal refrigerator must not be turned on or off for more than a certain time limit; therefore, the controller should have a view of the refrigerator's normal duty cycle, which is detected by a thermostat.

Controller: A controller (centralized or decentralized) is the central section of a demand management system. A digital filter is usually implemented in the pre-processing section. The time delay of this filter is utilized as a barrier to prevent the unnecessary activation of decentralized demand management systems during fast and short-term transients in power system.

Actuator: An actuator, such as smart switches, is in fact the part of the load control system that realizes control decisions into action (turning the load on or off).

Power source: A source of power supply is necessary for both the electrical loads and their controllers.

Communication network: The necessity of a communication network totally depends on the structure of the control method (centralized or decentralized).

5. Demand side control algorithms

Demand side participation in frequency regulation in power systems is planned according to two distinct general classes of control algorithms: centralized and decentralized control methods [28–30].

In centralized control algorithms, a higher level controller in the control hierarchy creates commanding control signals for lower level entities. Hence, a reliable two-way communication network is required to transmit data and control signals. Automatic generation control, phase shift transformers' controllers, and daily programming of major generation units, and most cases of demand response are examples of centralized control structures in power system. There has also been a considerable interest in possible applications of centralized demand management algorithms in smart grids. While, centralized control systems present a high degree of controllability (over lower level entities) and reliability, they own a disadvantage; namely, the economical cost of establishing and maintaining a secure communication network. This disadvantage becomes a huge burden especially when the number of participants in the control process is great. Thus, in a demand side contribution to frequency regulation program, in which the number of participants (i.e. controllable loads) might reach thousands or millions, the task of installing a reliable two-way communication network is particularly difficult (unless of course current basic infrastructures such as internet are utilized for that purpose).

In decentralized control approaches, unlike centralized control methods, control decisions are made by local individual controllers, usually using local measurement units (a distributed

measurement system). Thus, a decentralized control structure does not require a reliable and secure communication network (in some cases a primitive one-way network is needed to be able to update controllers' parameters). Based on the fact that a decentralized controller essentially relies on limited and local data, one can say that the amount of data processing for each controller is positively reduced compared to huge data processing burden of a centralized controller. Primary frequency control (droop), reactive power support in distribution systems, and digital protection relays are examples of decentralized controllers in power systems. It is obvious that absence of a communication network in a decentralized control environment is a considerable privilege over centralized approaches. Decentralized control approaches have been gaining scientific interest in recent years. This area is closely connected with multi-agent systems: each controller can be thought of as an individual with local means of perceiving its environment (local sensors), a "thinking" process to make decisions (control algorithm), and altering its environment by putting those decisions into actions (control process). Hence, in a decentralized control structure, as in a multi-agent system, collective behavior of individual agents will be definitely interesting and worth noting. We will cover this issue in a later part of this paper.

But certain complexities might arise regarding local measurement units. In demand management systems, local measurement of power frequency signal with proper precision is a hard task. Frequency measurement units, for power distribution level applications, are still too expensive to be able to be employed in great extents.

In the two following sub-sections, a thorough review on different load control algorithms (for participation in frequency control) is presented. The first sub-section discusses centralized control methods, while the second one is comprised of decentralized approaches.

5.1. Centralized control algorithms

Centralized demand contribution to primary frequency control has been put to the test in southern California. It is demonstrated that residential air conditioner systems (SmartACs) are perfectly capable of improving power system's reliability right after contingency occurrence. The communication structure, through which on/off control signals are transmitted to smart load switches, is discussed in details in Ref. [31]. It is obvious that for a small scale demand management program (to obtain frequency support), a centralized control strategy is economically preferable.

In Ref. [32], a centralized control strategy is developed and successfully simulated in a microgrid with considerable penetration of wind power. This algorithm considers three different operational modes for the power grid based on the magnitude of frequency deviation and system's previous status. When a contingency is detected (i.e. the system move into a certain critical operational mode), a central controller (with adaptive hill climbing technique) is activated and decision is made on total amount of required load response. Control signals are then transmitted to individual controllable loads via communication links to supply the grid with decided level of demand response. The effect of communication network latency on efficiency of the proposed management system is also studied. It is shown that when the latency surpasses 500 ms, system frequency becomes unstable, thus demonstrating the need for a fast communication network to maintain system stability. The communication system used in the paper is a wireless network that its latency lies safely under this limit (20 ms), but as the paper claims this might not be the case for today's everywhere-existing infrastructure.

Another centralized approach to demand side regulation during power contingencies is presented in Ref. [33]. A direct load control algorithm for thermostatically controlled space heaters is established and simulated. This algorithm utilizes a priority listing method based on current room temperatures, and by forecasting future states of participants (space heaters), control signals are sent to individual loads via a two-way communication network. It is obvious that the central controller should have access to room temperatures to be able to determine a space heater's capability (priority) to contribute to frequency control; thus, local household state measurements are also sent back to the central controller via the same communication network.

A centralized reserve provision algorithm using demand response is developed in Ref. [34]. After a power contingency, the central controller estimates the disturbance magnitude by means of initial ROCOF (the disturbance level is estimated to be linear function of ROCOF). Based on severity of the system status, the total amount of required demand response (along with spinning reserve) to counteract the contingency is then calculated. According to the estimated reserve requirements, controllable loads are directly turned on or off to avoid system collapse. The total controllable demand side reserve is classified into three groups: the size of the primary group is calculated according to the estimated worst credible contingency. This primary group is activated to limit the initial frequency drop above 59.2 Hz (in a system with nominal frequency of 60 Hz). The second group's task is to participate in frequency recovery and bring it back to 59.7 Hz. And the role of the third and the last group is to eliminate frequency steady state error. Based on the estimated severity of power contingency, these three groups of controllable loads are activated through a multi-stage decision plan. Simulations confirm that this algorithm is fully capable of restricting frequency deviations within predefined limits under different scenarios (both worst-case and medium-case contingencies are simulated).

5.2. Decentralized control algorithms

Decentralized demand control methods, regarding power frequency regulation, cover a wide range of technical papers, even though their application is still restricted in practice (due to expensive frequency measurement units). Frequency adaptive power energy rescheduler (FAPER) to obtain frequency reserve from electrical demand side was first proposed in Ref. [35]. There, it is even suggested that in long terms, decentralized demand contribution to frequency control merits the possibility of replacing central control of thermal units (AGC) to provide spinning reserve. Also, general marketplace and pricing issues are discussed.

In Ref. [36], another decentralized load controller (with local measurement unit) is presented; according to which, a fixed frequency threshold control system is proposed. This means that if system frequency deviation exceeds a certain limit (a preset constant), control action is exerted. The control algorithm uses two different thresholds for activation (contribution to frequency control) and deactivation (restoration to pre-contingency status) to avoid oscillations in frequency signal.

Another notable scheme is shown in Ref. [37]. In this plan, a power system stress detector is employed to keep control actions in a logical proportion with contingency level (i.e. action is exerted when necessary).

While simple frequency threshold control systems rely solely on frequency measurements (and are therefore single variable functions), in Ref. [38] a fixed, two-variable threshold function is presented to be installed on individual refrigerators. This proposed decentralized control plan is simulated and tested in a power system without spinning reserve and with considerable penetration

of wind power. The two-variable threshold function is a linear combination of frequency deviation in power system and refrigerator temperature and therefore serves a double-aspect procedure: on one hand, when system is in normal conditions the threshold function is a simple thermostat; on the other hand, when a frequency deviation occurs, the threshold function acts as a demand management system for frequency reserve provision (according to each refrigerator's inner temperature, activation threshold is allocated in frequency-temperature plane). The simulations demonstrate that a 36000 MW system, with a total amount of 1320 MW frequency-sensitive refrigerators, can restrain system frequency (with nominal value of 50 Hz) above 49.8 Hz, while the frequency of the same system without frequency responsive loads, drop below 49.5 Hz, facing the same contingency. The aggregate deferred energy of participating refrigerators can be paid back to restore pre-contingency balance among them. Also, by comparison with conventional generation side reserve provision, the simulations show that this approach is environmentally beneficial.

A fuzzy logic load controller, using frequency signal and ROCOF as input variables, is proposed in Ref. [39] for a power system with high penetration of renewable energy resources. It is stated that using fuzzy logic is especially effective when utilized as demand management system; since from demand side's perspective there is a certain level of uncertainty, considering power system's unknown basic characteristics (i.e. decentralized load controllers do not have access to system's overall operational information). The algorithm was tested on a micro-hydro single phase energy network (with a maximum capacity of 18 kW) in the UK. It was observed that the load control scheme was able to limit frequency deviations within ± 0.2 Hz (with a total amount of 15 controllable 1 kW loads). The test was repeated under varying wind speed with satisfying outcomes.

A time-dependent frequency threshold control system is presented in Ref. [40]. Control decision is made by means of a semi-inverse frequency-time curve, quite similar to the over-current protection of power lines. By assigning (according to their innate functions in a house) different semi-inverse curves to different groups of loads, dissimilar demand response can be achieved from various groups of loads to a frequency excursion. The time-dependency of activation threshold is an indication of control system's close association with power systems dynamical state after contingencies. A state machine is also used to consider essential delays before or after exerting the control signal to the switch. It is demonstrated that under the proposed demand management system, frequency reserve is procured according to a droop curve, similar to that of a synchronous generator. In Ref. [41], the same semi-inverse curve is employed to verify the effectiveness of domestic demand side participation in frequency control; this paper demonstrates that in an energy network with a high penetration of uncertain wind power (20% of the whole power generation), demand response is able to enhance the quality of frequency control considerably. With a penetration of 10% controllable electrical demand of domestic type, the worst case primary frequency drop (in face of a major generation loss) can be decreased from an unacceptable amount of 2.115–1.14 Hz. It is shown that along with higher magnitudes of frequency deviations, the participation rate of demand side is also effectively increased; thus, when the deviation reaches a high level of 1.11 Hz, the participation rate is effectively increased to 65%.

A state machine is also employed in Ref. [42] to control loads' switches. The proposed decentralized control algorithm is a fixed threshold system. But types of domestic loads are classified based on their importance in consumer's daily activities, and different thresholds are assigned to these groups based on their essentiality. For example, the activation threshold assigned to high priority lighting load controllers (48.9 Hz) should obviously be lower than the one assigned to low priority refrigerators (49.7 Hz); thus, lighting loads' contribution to frequency control is more limited than the refrigerators and restricted only to the most sever power losses. An interesting simulation was presented at the end of the paper, by modeling Great Britain's (GB) energy network. According to the paper, presently GB's energy network capacity is around 41 GW and its inertia constant is an estimated value of nine seconds, with an anticipated worst case power contingency level of 1320 MW. However, it is predicted that in 2020, system inertia will be reduced to three seconds (due to expected higher levels of renewable energy resources), with a critical anticipated worst case power loss level of 1800 MW; therefore, it is obvious that additional measures are necessary to maintain system stability. After introducing the proposed demand response algorithm into the simulation, it is concluded that for the present system, under this specific load control strategy, approximately a total size of 200 MW controllable demand is required to restrain system frequency above 49.5 Hz, under a power loss of 1320 MW. However, for the future energy network, because of its predicted critical condition in this respect, around 1000 MW reserve on demand side is necessary to keep the frequency over 49.5 Hz, for the worst case scenario (1800 MW power loss).

An experimental implementation of a low-cost decentralized load control system was introduced in Ref. [43]. This experiment was set on Bornholm Island with a small power grid, which enjoys high penetration of wind energy (33%). Around 70 controllable electrical appliances (thermostatically-controlled and relay-controlled) were equipped with these control devices to enable them to respond to frequency deviations, at which time their behavior was monitored. According to the results of the test, the frequency-sensitive loads are positively capable of providing both normal and disturbance reserves. Although the experiment is only considering a small population of participants, it demonstrates that the average contribution of loads to frequency regulation can be significant, relative to their actual size. For example, frequency-sensitive refrigerators can cut 46% of their average power when system frequency falls below 49.85 Hz, which is a substantial amount. While this experiment and other mentioned practical experiences with participation of controllable loads in frequency support provide positive outcomes, one should not forget that because of the nonlinear and complex nature of energy networks, higher penetration of active loads into the grids might introduce major difficulties which must be addressed carefully. Thus, in the next section (section 6), we will discuss the collective behavior of controllable domestic loads along with the various proposed techniques to limit their potentially destabilizing effects.

5.3. Centralized vs. decentralized algorithms

In this subsection, we will give some brief concluding points on the two load control strategies. As described before, centralized management approaches offer increased levels of controllability, since the higher-level control centre has direct access to all the domestic appliances throughout the grid. Thus, it might be thought that system stability and security are improved significantly, by eliminating the possibility of erroneous measurement and control. However, this improved security comes at the expense of a communication system with considerable maintenance and technical issues. While the establishment of such a communication network might be possible and beneficial in systems with relatively small size or low penetration of controllable loads, it might pose a heavy technical and financial burden on large power systems with hundreds of thousands of controllable domestic loads. Many algorithms, that we have encountered, depend not only on frequency and power measurement but also on local internal data, such as room temperature and refrigerator

air temperature. When the number of controllable loads is significant, sending all of these local measured data to one central controller to process might be impractical. Besides, due to the heavy burden of centralized signal processing, a minor change in the parameters of the system or loads may result in troublesome major revisions in the algorithm. Some other algorithms (which will be discussed in next section) exploit random processes to introduce disparity among loads. Implementation of these algorithms with centralized strategy results in a complex computational task, which also requires major revisions when new clusters of loads are added to the demand response program. Thus, a decentralized approach with its plug-in nature and parallel control action seems to be a more reasonable option, in these cases.

On the other hand, decentralized control strategies depend on local measurement and decision making actions on electrical distribution level, which might be more erroneous and unreliable due to noise or unnoticed inner faults in devices. Frequency measurement devices with enough precision and reasonable cost are not yet available everywhere. Moreover, even the most purely decentralized algorithms may need basic communication links, in order to enable necessary corrections along time. Also, note that decentralized control approaches are still the topics of fresh ongoing academic researches, and their merits and capacities are probably waiting to be discovered in future.

Hence, the problem of choosing a centralized or decentralized approach evades general solutions and depends on the each special case's formulation: economic and financial specifications, the possibility of establishing a communication network, and the technical details of the preferred load control algorithm itself.

6. Synchronization

Synchronization phenomenon is a case of emergent behavior in complex systems and has been reported in natural and artificial systems [44]. Complex systems are systems composed of a high number of agents or elements. An element in a complex system undergoes certain changes in its dynamical states through some local transition rules (control logic). These transition rules are multi-input functions, which take neighboring elements' states along with current agent's states and environmental conditions (local measurements) as control inputs and generate future dynamical states of the agent [45]; thus, there is a certain degree of coupling among neighboring agents in the complex system. Under specific circumstances (usually when a local control variable exceeds a certain limit), a phase transition occurs and the collective behavior of the system takes on a recognizable structure; this emergence of order is in fact a qualitative change (i.e. bifurcation) in aggregated dynamic of the system. Synchronization is a renowned case of collective order in complex systems. A noteworthy characteristic of emergent order in complex systems is nonlinearity. This means that one cannot elicit the changes in collective behavior of the system by only considering the dynamics of each agent or element alone; thus, unlike linear systems, in which the whole system is a linear magnification of each part, in a complex system, due to the couplings among the elements, the linear amplification of an element's output does not represent the collective behavior of the system.

Synchronization takes place in multi-agent systems in which individual agents (elements) can be modeled as oscillators (i.e. they have periodical working cycles). When there is no synchrony in the system, oscillators operate near their individual natural frequencies (but of course, because of minor effects of the couplings, their operational frequencies differ slightly from their natural frequencies). But under certain conditions, working frequencies of a large cluster of oscillators spontaneously lock into a common value and a definite form of order arises, which is called synchronization [46,47].

In a power system, synchronization among thermostatically controlled loads is possible [48–51]; since refrigerators and space heaters have periodic working on/off cycles, they can be looked upon as oscillators. During normal operation of power system, these oscillators act independently (low level of coupling). Thus, load profile under normal conditions is a relatively flat curve. But under certain circumstances, working cycles of these loads (oscillators) get locked to each other; this means that large clusters of thermostatically controlled loads turn on and off simultaneously. This emergent synchrony leads to considerable long-term oscillations and overshooting in overall demand curve and consequently in frequency profile. Apart from the fact that these oscillations lead to unnecessary frequency control activation and reserve exploitation in the energy network, they might even cause instability and system failure.

6.1. Synchronism in cold load pick up

Early cases of synchronization in power systems were reported during the cold load pick up phenomenon [52,53]. “Cold load pick up” refers to the sudden increase in demand profile level after long power disruptions, especially in winters, when consumers are relying on electrical space heaters, after the power disruption, the temperature of the houses face a simultaneous decrease due to cold weather. After the reconnection of the loads to the grid, a collective effort by space heaters in the area takes place to bring back the house temperatures to normal range; this means that space heaters should be in “on” state simultaneously and for a considerable interval. The simultaneous turning on of the space heaters results in a sudden increase in demand curve (cold load pick up), which might have a harmful effect on voltage profile of that area. Apart from the mere increase in heating demand level, cold load pick up is also marked with oscillatory behavior of collective loads’ profile, before it returns to pre-disruption level. The level of the oscillations depends on the duration of power disruption, diversity of load and control parameters in the system. It is obvious that the oscillatory behavior of heating demand power, during load pick up, is the consequence of partial and decadent synchronism among the residential thermostatically controlled space heaters.

6.2. Synchronism after demand contribution to frequency control

When talking about demand side contribution to frequency control, one must carefully consider the effect of synchronization in power system. Improper design of load control algorithms might precipitate an unwanted synchrony among thermostatically controlled participants and cause system failure.

Since contribution to frequency control requires that clusters of controllable residential loads be turned on or off simultaneously, it is essential to investigate the long-terms effects of such collective behavior on power system. In case of participation in frequency regulation, under critical conditions, synchronization takes place “after” the power contingency has been eliminated. Thus, when participants in frequency control program (i.e. controllable loads) are switching back to their normal operational cycles, there is the considerable possibility of simultaneous turning on or off for large clusters of loads. This simultaneous cycling leads to long-term oscillations in power frequency signal and might even trigger load controllers again, without an actual necessity; in which case, system restoration to pre-contingency conditions is hampered and its stability is jeopardized. Hence, some measures must be considered to “desynchronize” controllable thermo electrical loads, when they are being restored to their normal operation.

This desynchronization process is a vital part of designed demand management systems aimed to provide frequency reserve. In fact, the heterogeneity of the population of controllable loads plays a crucial role in restricting and dampening the oscillations; however, as will be discussed later, it is shown through simulations, that even in that case, the existence of a designed desynchronizing algorithm is necessary.

A desynchronization procedure is usually a random process. Its randomness guarantees the highest possible degree of non-simultaneous cycling among thermostatically controlled loads. There are insightful instances of decentralized desynchronization methods proposed in literature. A random delay reconnection configuration is proposed in Ref. [40]. According to this method, when system frequency has been restored to nominal value, controllable loads switch back to their normal operational cycles after being subjected to a random time delay (chosen in a reasonable interval based on a uniform function). By means of random time delays, simultaneous reconnection of loads to the system is avoided and the possibility of synchronization is minimized.

In Ref. [48], synchronization is studied through a multi-agent system approach. By means of numerical simulations of a heterogeneous population of refrigerators (with fixed threshold control system), it has been demonstrated that possibility of system failure due to synchronization of controllable loads (after participation in frequency regulation) is evaluated according to an S-shaped curve. This S-shaped curve is a function of level of penetration of controllable loads in the system (which means that increasing the penetration of controllable thermo-electric loads implies higher probability of system failure due to synchronization). Note that according to the results of the simulations, system failure due to synchronization is possible even in case of a heterogeneous population of refrigerators. A random load restoration threshold system is proposed to avoid synchrony. Unlike using random time delays, here, electrical loads switch back to their normal working cycles, when frequency deviation goes below a certain random threshold. In this way, similar and simultaneous cycling of loads can be avoided and a smooth demand response is achieved.

Another synchronization-based study of demand side contribution to frequency regulation is presented in Ref. [49]. A stochastic model based on Markov chains is developed to describe the collective behavior of population of controllable refrigerators in a power system. Each appliance can be modeled as a two-state (on/off) Markov system. The transition probabilities between these two states (which actually determine the switching rate of the refrigerators) define the average duty-cycle and the average temperature of the device. Based on this model, it is shown that desynchronization could be achieved by defining certain control parameters (such as average desired temperature or average duty cycle of the refrigerator) as a linear function of system frequency deviation from the nominal value. These control parameters are then used to compute the optimal switching periods for refrigerators. Various versions of this decentralized control algorithm are tested and their efficiency in regulating system frequency is assessed via numerical simulations. The simulations prove that this stochastic demand side energy management approach is capable of curtailing the frequency overshooting and avoiding long-term oscillations compared with deterministic fixed threshold method. It is also analytically demonstrated that even in the case of identical (homogeneous) domestic appliances (refrigerators), the system (with the proposed random decentralized approach) is locally asymptotically stable.

Since Markov chains are not able to precisely model the behavior of heterogeneous population of appliances, a more realistic modeling of aggregated dynamics of heterogeneous population of domestic space heating is presented in Ref. [54]. In this paper, the collective behavior of HVACs is obtained by means of second-order Equivalent Thermal Parameter (ETP) modeling. The ETP model for each device is an equivalent thermal circuit, which is used to obtain states-space representation of a single appliance. Using this representation, the flow of population of on and off devices is tracked on a two-dimensional grid. The two parameters that build up the space, on which the grid is based on, are room air temperature and inside mass temperature (furniture, walls, etc.). In order to model the heterogeneity of loads, according to their parameters, they are regrouped into distinct homogenous clusters, using k-mean technique. The model is shown to perform well under various operational conditions. The paper, also, introduces an innovative centralized load control, which seems to significantly reduce demand profile overshooting and oscillations, compared with sudden load drop. In this control algorithm, instead of sending a deterministic on or off signal to participants, a signal with magnitude of less than one is sent to demand side. This signal defines the probability of switching the loads on or off (based on the sign of the signal), thus introducing a stochastic process in the centralized demand management scheme. The effect of HVAC compressor time delay is also considered. The numerical simulations demonstrate that this method is capable of procuring a smooth response and damping partial synchronization on demand side.

In Refs. [51] and [55], it is shown that identical demand side control logic for all domestic appliances results in frequency oscillations (synchronization problem). Thus, a random process is included in control algorithms to overcome this effect. This random process takes advantage of discrete monitoring time instants for domestic loads (i.e. it is assumed that each load controller monitors system frequency on random time steps), thus creating a Poisson response function for the appliances. It is demonstrated that if demand response exceeds a certain threshold, occurrence of frequency overshoot is probable. The approximate probability of the frequency overshoot is then computed; it is shown that in order to decrease the probability of frequency overshooting, the response rates of the controllable loads should be reduced, at the expense of average frequency recovery time; therefore, a calculated compromise among these two essential parameters (i.e. frequency overshooting and recovery time) is necessary. The compromise can be made through an S-shaped curve, which shows the relation between them. The paper also presents an interesting case of simulation; the proposed load control method is applied to Irish power grid (with the radical assumption of deactivating generation side frequency reserves). With only 2% of the total electrical demand being controllable (117.5 MW), during a power loss of 50 MW magnitude, the frequency deviation can be restricted within 0.1 Hz, and the system can be recovered in 15 s.

Another study of synchronization is presented in Ref. [50]. In this paper, which also relies on random deactivation time delays to dampen partial synchronism, the effect of changing the range of random number selections on the amplitude of frequency oscillations is studied, through numerical simulation of power system with heterogeneous groups of domestic loads. As analytically demonstrated in Ref. [55], and also in this paper, widening the time delay ranges (i.e. lowering the rate of deactivation) results in decreased frequency overshooting (because of the decrease that is caused in the average density of appliance switching); however, a considerable time lag is created (system recovery is delayed).

7. Conclusion

This paper investigated demand response methods to provide frequency reserve in energy networks. Different centralized and

decentralized algorithms were reviewed and studied, according to which, electrical demand side can be considered as a reliable source of ancillary service provision in modern power systems with high penetration of renewable energy sources. The problem of demand side synchronization in thermostatically controlled loads was also discussed and proposed stochastic methods to prevent it from happening were briefly studied. However, there are still some problems that are not yet properly addressed. As a suggestion for future research, trying to present an analytical model of synchronization among thermostatically-controlled loads, in order to provide a better understanding of this phenomenon, may be challenging and necessary. Since most papers on this issue rely heavily on numerical simulations, there are reasonable doubts within the power engineering community about the seriousness of the effects of synchronization. While many papers, as discussed in section 6, focus extensively on curtailing harmful side-effects of synchronization by means of random processes, others like Ref. [38], report that, despite their former reservations, no serious oscillations are observed in numerical simulations. Thus, looking for an analytical foundation to inject more certainty into this matter might be of interest. However, the authors are well aware of the difficulty of analytically tracking nonlinear complex systems, which usually requires impermissible simplifications at the expense of dismissing the emergent behavior of the complex system; therefore, the task might be more complicated than it seems to be.

Another conceivable research problem is the introduction of demand side contribution to frequency control in an interconnected multi-area system. While most papers, so far, have concentrated on demand side reserve in single area energy networks, multi-area systems pose more serious problems, especially when the secondary frequency control stage is concerned. Hence, when we are dealing with a multi-area system with high penetration of controllable loads (and particularly when these loads are able to contribute to secondary frequency control level), a thorough analysis on dynamic performance and stability of the system is necessary.

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